

# **The Scientific Bases of Sustainability: Methods, Measures and Correlations**

*Le basi scientifiche della sostenibilità: metodi, misure e correlazioni*

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## **Abstract:**

Defining and assessing sustainability of complex systems (ecosystems, production systems, territorial systems, etc.) is a crucial challenge for modern science. Several instruments are necessary to answer a lot of questions related to the interactions between man and Nature. Policy makers, businessmen, researchers, managers, environmentalists and common people need information in order to understand what is sustainability and what is the distance of their behaviours from it. Sustainability indicators have been developed with the purpose to answer all these questions.

The paper presents the results of the SPIn-Eco project, a sustainability analysis of the Province of Siena (Italy). It has produced a data set that allows a practical comparison among several approaches and indicators by means of correlation analysis. Important correlations were found between Ecological Footprint and CO<sub>2</sub> emissions as well as with the non renewable exogenous part of Emergy flow. No correlation was found between total emergy flow and total ecological footprint.

**Keywords:** emergy evaluation, ecological footprint, greenhouse gases balance, correlation analysis, sustainability.

## **1. Introduction**

In the editorial of Ecological Economics n. 44, Paul Ekins, Carl Folke and Rudolf De Groot (2003) wrote: *In November 1990, at a cafe' in the central square of Siena, Italy, the theme of the upcoming ISEE (International Society for Ecological Economics) conference in Stockholm in 1992 was discussed. The working title of the conference "Maintaining Natural Capital" did not really capture the essence of the issues to be raised. In an intense discussion Herman Daly suddenly proclaimed "Let's use 'Investing in Natural Capital' instead"*.

Nature is crucial for human life but only in the last decades Natural Capital is considered something more than a mere production factor.

*Investing in Natural Capital* and managing natural resources are key problems for every modern society. Any environmental, economic or urban program or plan, both at local and global level, has to pay attention to the correct use of them in time. According to the statements of Herman Daly (1990), there are some resources-use criteria to follow in order to reach a sustainable society which is founded on a sustainable economic basis as well: renewable resources should be managed so that they are neither depleted nor

degraded; non-renewable resources should be extracted at a rate that does not deplete them before technology and industry are able to shift to suitable renewable substitutes; pollution and wastes must be emitted no faster than natural systems can absorb them, recycle them, or render them harmless.

Sustainability is a concept that requires a clear focus towards a scientific assessment and quantification. In order to reach the optimal point described by Daly's principles, all social and economic subjects, and the whole society as well, have to implement the most suitable conditions to do it, starting from a good level of information. Here the scientific research operates by providing theories, instruments and objective knowledge so that the decision makers are able to imagine present and future development.

The needs of sustainability are met if an iterative chain of steps is clearly designed and finally realised and there is a growing interest in instruments that enable it: sustainability indicators. They are able to describe a biophysical model of the economic process where capital and labour are intermediate inputs provided by the only primary production factor, Natural Capital (Tiezzi and Marchettini, 1999).

All data and results presented in this paper are from the SPIn-Eco Project (2001-2005), a research program with the purpose of assessing the environmental conditions of the Province of Siena (Tuscany, central Italy) and its 36 municipalities. It is a deep analysis of the state of the territorial system by a complete set of instruments and indicators. The indicators used in this paper are linked to the following methodologies: Emergy evaluation; Ecological Footprint analysis; Greenhouse gases Inventory.

## **2. Methods**

### **2.1. Emergy analysis**

To take into account all the resources (natural and manufactured) sustaining a system, we adopt the concept of Emergy introduced by H.T. Odum (1988, 1996). He defined emergy as the quantity of solar energy necessary (directly or indirectly) to obtain a product or an energy flow in a given process. Emergy is the common basis on which a system of environmental accounting can be built. It is the memory of all the solar energy necessary during the process to make a resource available. It is measured in Joules, but not indistinct Joules, solar emergy Joules (sej).

To convert all the inputs in sej, the concept of Transformity is introduced. Solar Transformity is defined as the emergy required per unit of product or service. It is the solar energy directly or indirectly necessary to obtain one unit of another type of energy. All the inputs are classified in renewable (R) and non-renewable (N) resources and local (L) (natural) and imported (F), then some indicators of environmental stress can be calculated.

The Environmental loading ratio (ELR) is the ratio of non-renewable (local and imported) emergy to renewable environmental emergy. The Emergy per person (EpP) is the ratio of total emergy to the inhabitants of the system. The Empower Density (ED) is the ratio of total emergy to the area (expressed in m<sup>2</sup>). The Emergy yield ratio (EYR) is the ratio of total to purchased emergy.

## **2.2 Greenhouse gas Inventory**

As a result of increasing warnings by members of the climatological and scientific community about the possible harmful effects of rising greenhouse gas concentrations, the IPCC was established by the World Meteorological Organization and the United Nations Environment Programme in 1988 to assess the available scientific, technical, and socioeconomic information in the field of climate change.

The resulting Kyoto Protocol established a reduction of emissions for developed nations, with respect to their emissions levels in 1990.

The anthropic emissions of greenhouse gases have global implications in terms of sustainability. According to the IPCC guidelines (1996), energy, agriculture, land-use change and forestry and waste are monitored. The main result is the comparison between the emission of equivalent CO<sub>2</sub> and the absorption capacity of the ecosystems inside the territory. The inventory includes emissions of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, CO, NMVOC (non-methane volatile organic compounds), SO<sub>2</sub>, HFC, PFC, SF<sub>6</sub> and the absorption of CO<sub>2</sub>.

## **2.3 Ecological footprint**

The Ecological Footprint (EF), UNEP-WCMC e WWF (2002), developed by Wackernagel and Rees (1996), Monfreda et al. (2004), Bagliani et al. (2003) in the nineties, is a measure of the consumption of renewable natural resources by a human population of a country, a region or the whole world. A population's EF is the total area of productive land or sea required to produce all the crops, meat, seafood, wood and fibres it consumes, to sustain its consumption and to give space for its infrastructure. It is interested, to compare the concept of ecological footprint with that, more used, of carrying capacity. This latter quantity is defined as the maximum weight, exercised from the population of a defined species, that a region can support without irreversibly compromising the productivity of the region itself. The ecological footprint represents the portion of carrying capacity used by the human population living in region. The ecological footprint analysis reverses the concept of carrying capacity evaluating the productive territory effectively used by a population, wherever this surface may be located (inside or outside the region under consideration), instead of the maximum human population that the area can support.

The EF classic formulation considers the average consumption of the population, based on the assumption that use of energy or matter derives, directly or indirectly, from a certain extension of land, hosting the ecosystems that support the resource drawing and/or guarantee the absorption of the emissions.

Available biological capacity is the total biological production capacity per year of a biologically productive space, expressed in global hectares. The ecological deficit is the difference between EF of a population and biological capacity of the space available to that population. This indicator measure the amount by which the area's footprint exceeds the ecological capacity of that system.

## **2.4 Correlation analysis**

A correlation describes the strength of an association between variables. An association between variables means that the value of one variable can be predicted, to some extent,

by the value of the other. A correlation is a special kind of association: there is a *linear* relation between the values of the variables. A non-linear relation can be transformed into a linear one before the correlation is calculated.

For a set of variable pairs, the correlation coefficient ( $R^2$ ) gives the strength of the association. The square of the size of the correlation coefficient is the fraction of the variance of the one variable that can be explained from the variance of the other variable. The *relation* between the variables is called the *regression line*. The regression line is defined as the best fitting straight line through all value pairs, i.e., the one explaining the largest part of the variance.

In formulae:

$$y = \alpha + \beta x + \varepsilon \quad (1)$$

where  $x$  and  $y$  are the independent and dependent variable, respectively;  $\alpha$  e  $\beta$  are the regression coefficients and  $\varepsilon$  is the error.

$$R^2 = \frac{Cov_{xy}^2}{Var_x \times Var_y} \quad (2)$$

### 3. A case study: the Province of Siena and the SPIn-Eco project

The Province of Siena is located in Tuscany, central Italy. It is one of the largest provinces in Italy and the second largest province in the Tuscan region. It is 3821 km<sup>2</sup> with a relatively low population around 250.000 people, making the density around 66 inhabitants per square kilometre. The Province's main commercial activities stem from the tourism, trade, banking and agricultural sectors; there is very little industrial activity. The province's principal commercial products are wine (Brunello di Montalcino, Chianti, Vino Nobile di Montepulciano and Vernaccia from San Gimignano), cheese and olive oil.

From an environmental point of view, the Province of Siena is a quite peculiar system. In fact, even though in a context of an industrialized country, it does not present the negative aspects generally related to this type of development. The low density of population and the careful attention to the natural and historical heritage make the Province of Siena an example of "different" development, as also stated in the OECD report (2002). In 1999, the GDP per capita was 17,822 euro.

The SPIn-Eco project (Sustainability in Province of Siena through Ecodynamic Indicators) is a research program funded by the Siena Province administration and by the Monte dei Paschi Foundation with the purpose of assessing the environmental conditions and the relative level of sustainability of the Province of Siena (Tuscany, central Italy) and of the 36 municipalities within. It is a deep analysis of the state of the territorial system by a complete set of sustainability indicators.

The Province of Siena is generally recognized to be an area with a good harmony between human activities and environmental quality. Why it is important to study the level of sustainability such an area? First of all because the results of an in depth analysis can give responses that are not in accordance with the general perception. This happens, for instance, when an area is characterized by low levels of pollution but also by an irrational use of the resources. Our goal has been to assess the resource use and to

identify those aspects that could become limiting factors for the development of future generations. This project allowed the collection of a relevant data set of several indicators and the calculation of correlations among several indicators based on the above methodologies. These correlations are obtained for very homogeneous systems and there is the possibility to find that there is a redundancy in the use of indicators, leading to a simplification of the procedure of assessment of the level of sustainability of a similar areas.

#### 4. Results and discussion

SPIn-Eco project created a data set of the mentioned indicators (and others) collected and calculated in the 36 municipalities that compose the Province of Siena. Correlation plots between indicators is shown. Limitations of these correlations are due to the fact that the differences within the Province are not so relevant and thus there is a high degree of homogeneity.

As it is clear from the definitions, there is a good level of similarity between Emergy evaluation and Ecological Footprint analysis. The poor correlation between Emergy flow per year and Total Ecological Footprint, that is the Ecological Footprint multiplied by the population of the area are shown in Figure 1.

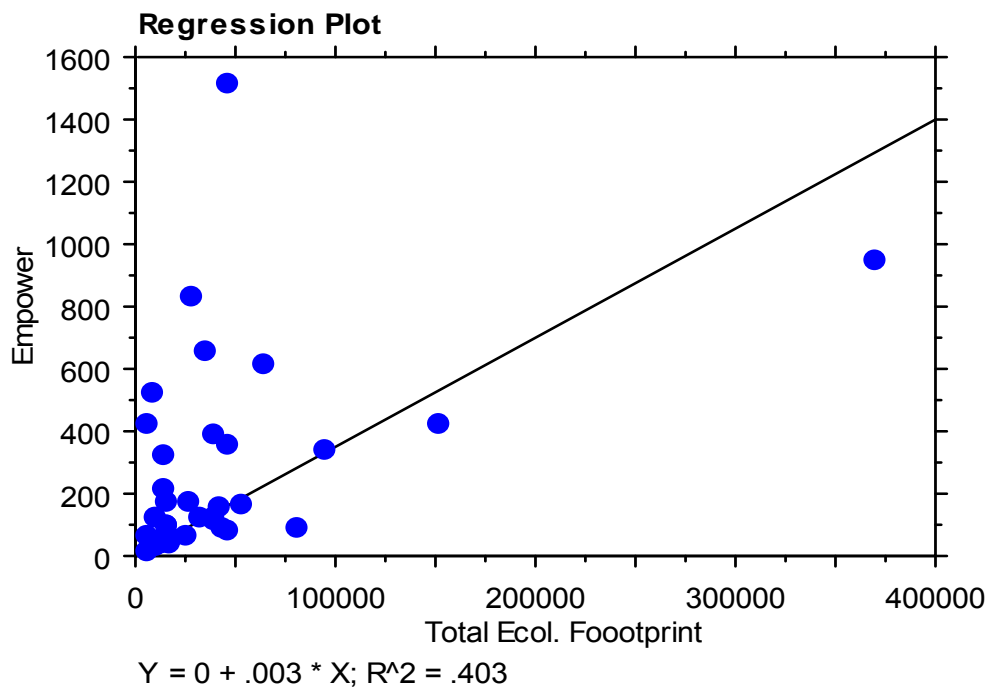


Figure 1. Correlation plot of Emergy flow (Empower measured in  $10^{18}$  sej/year) to Total Ecological Footprint (in hectares), that shows a  $R^2=0.403$ .

How could this occur? A first reason can be the fact that in the Emergy analysis, all the inputs, both natural (spontaneous) and artificial are considered, while the Ecological Footprint analysis considers only what is used for the population consumption. We have

tested the hypothesis that just the F part of emergy (purchased inputs from outside the territorial system) can be correlated with the Total Ecological Footprint.

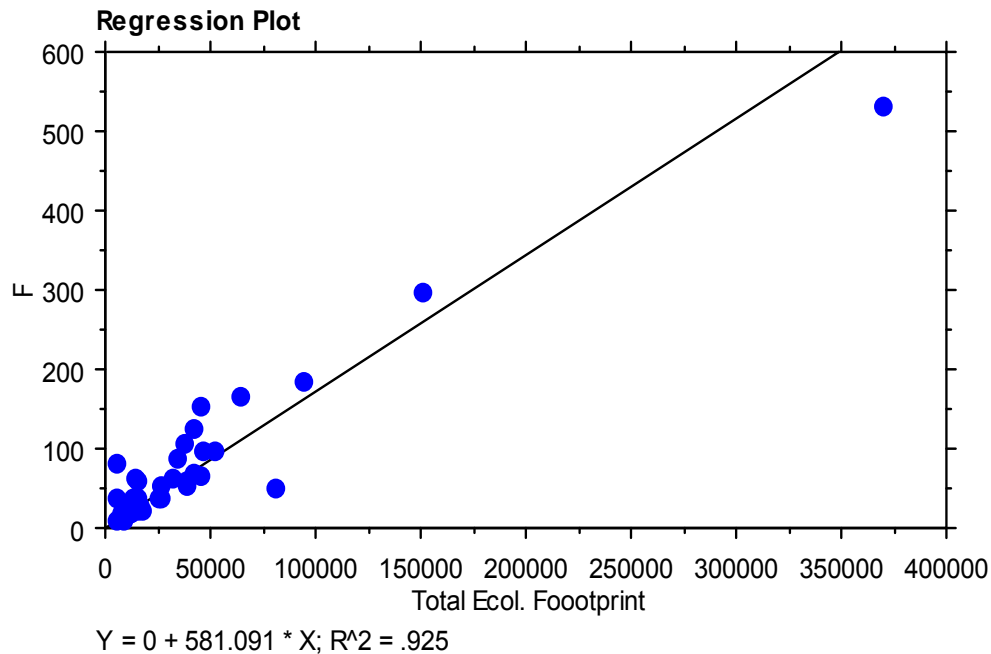


Figure 2. Correlation plot of F (non-renewable exogenous part of the Empower in  $10^{18}$  sej/year) vs. Total Ecological Footprint (in hectares), with  $R^2=0.925$ .

Figure 2 shows an almost perfect correlation between these two indicators, confirming the validity of the hypothesis. On the contrary, the correlation between R+N (local emergy flows, both renewable and non-renewable) and Ecological Footprint is negligible ( $R^2=0.179$ ). The common aspects of the F part of the emergy flow and the Ecological Footprint are, for example, the production of goods that are consumed and are included in the accounting system, independently on the fact that the goods are not locally produced, and the use of energy resources (both fuels and electricity).

Ecological Footprint considers (as a separate category) the “land for energy” that is what is required for the absorption of the greenhouse gases emissions. In the Province of Siena this part constitutes the 68% of the total Ecological Footprint (Bagliani et al., 2003). For this reason we have investigated also the correlation between Total Ecological Footprint and CO<sub>2</sub> emissions.

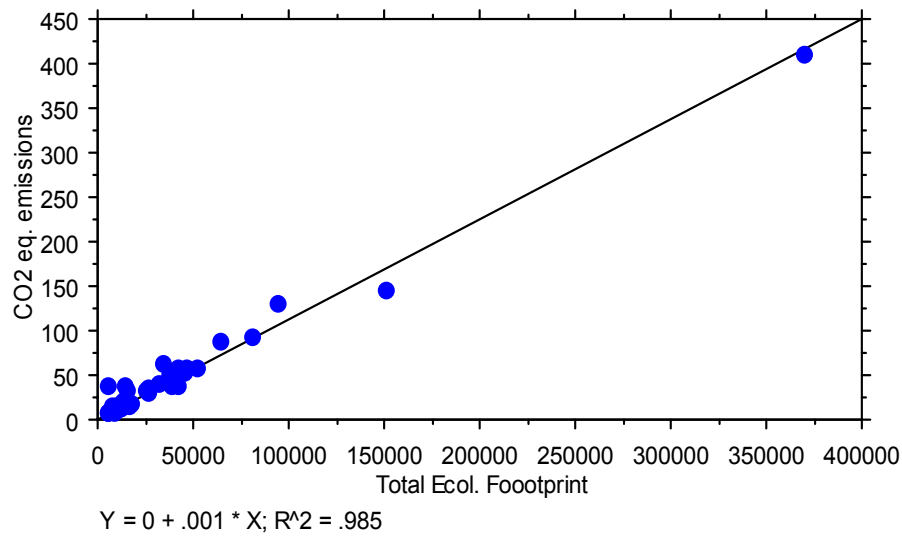


Figure 3. Correlation plot of CO<sub>2</sub> emissions (in Gg) vs. Total Ecological Footprint (in hectares).

The convergence of the two analyses is practically perfect ( $R^2=0.985$ ), probably due to the fact that the 36 points of the plot are taken in an homogenous region, where the difference in the pattern of consumption within the population in the municipalities is very little. Therefore the relevance of the “land for energy” is reflected in the strong correlation with the CO<sub>2</sub> emissions.

We have decided to check also the plot of F versus CO<sub>2</sub> emissions. The good level of correlation was expectable: F includes fuels, and electricity from the national grid and other imported goods and services that should be considered non-renewable since the indirect use of fuels is anyway relevant on the total of the energy required for their production.

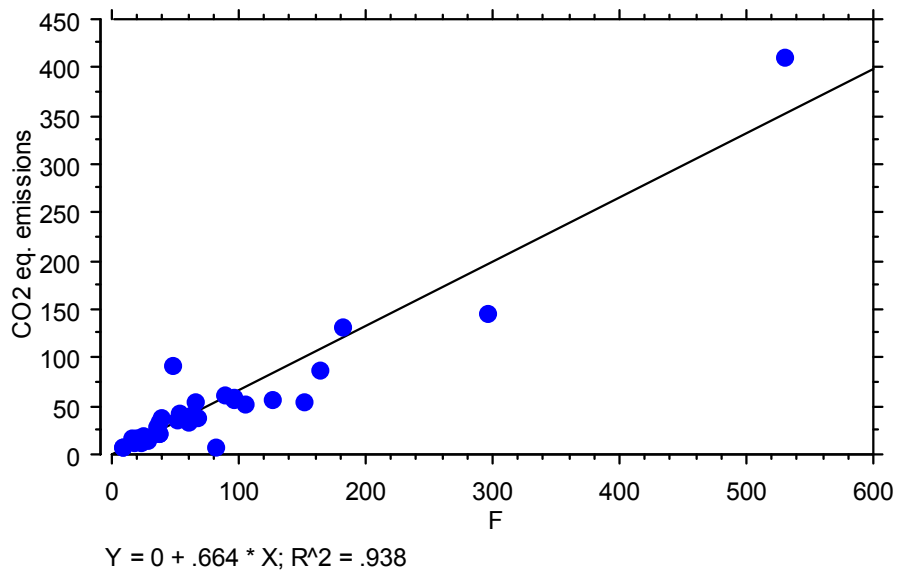


Figure 4. Correlation plot of CO<sub>2</sub> emissions (in Gg) vs. F (in  $10^{18}$  sej/year).

Nevertheless it is relevant to show that there is a better correlation of the greenhouse gases emissions with Ecological Footprint than with non-renewable exogenous emergy flow F ( $R^2$  is 0.938 in the latter case).

## 5. Conclusions

The sustainability analysis made during the SPIn\_Eco project has produced a data set that allows a practical comparison among several approaches. We have started with the main three indicators, trying to understand what is the level of overlapping/complementarity of these approaches. A first negative result is the lack of accordance between Ecological Footprint and Emergy flow. Even though the general aim of the two methods is similar, these indicators seem to be complementary, at least in part. In fact the non renewable exogenous part of the emergy flow correlates quite well with the Ecological Footprint, showing that the R and the N part of the emergy flow have practically no relation with the Ecological Footprint. This means that Emergy evaluation shows aspects related to the use of local resources (materials storages for example) that Ecological Footprint does not.

It is interesting to note that both F and Ecological Footprint have good accordance with the CO<sub>2</sub> emissions. This implies a good level of overlapping among the three indicators. For the calculation of Ecological Footprint a huge data base of personal consumption of the population is necessary. When it is not available, assumptions have to be made to reach a final result, that will be anyway less reliable. For the calculation of the F part of the emergy flow, the data set is very relevant and data are not always available or reliable.

We can therefore say that, in similar systems, as a first approximation, a greenhouse gases emissions assessment could substitute the Ecological Footprint evaluation or the calculation of the imported emergy flow. In fact the CO<sub>2</sub> emissions calculation is much easier and less time consuming than the other two.

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